

**Regional Stratigraphy of the South Polar Layered Deposits (Promethei Lingula, Mars):  
“Discontinuity-bounded” Units in Images and Radargrams**

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53    **Highlights**

- 54    - We defined a new regional stratigraphy of the SPLD in Promethei Lingula;
- 55    - The stratigraphic units are defined on the basis of defined discontinuities;
- 56    - The discontinuities have been mapped both in images and radargrams;
- 57    - The regional stratigraphy suggests climate and orbital changes on Mars in the past.

## 59   **Abstract**

60       The Mars South Polar Layered Deposits (SPLD) are the result of depositional and erosional  
61   events, which are marked by different stratigraphic sequences and erosional surfaces. To  
62   unambiguously define the stratigraphic units at regional scale, we mapped the SPLD on the basis of  
63   observed discontinuities (i.e., unconformities, correlative discontinuities and conformities), as  
64   commonly done in terrestrial modern stratigraphy. This methodology is defined as “Discontinuity-  
65   Bounded Units” or allostratigraphy, and is complemented by geomorphological mapping.

66       Our study focuses on Promethei Lingula (PL) and uses both high-resolution images (CTX,  
67   HiRISE) and radargrams (SHARAD) to combine surface and sub-surface observations and obtain a  
68   3D geological reconstruction of the SPLD. One regional discontinuity (named AUR1) was defined  
69   within the studied stratigraphic succession and is exposed in several non-contiguous outcrops  
70   around PL as well as observed at depth within the ice sheet. This is the primary contact between  
71   two major depositional sequences, showing a different texture at CTX resolution. The lower  
72   sequence is characterized mainly by a “ridge and trough” morphology (Ridge and Trough  
73   Sequence; RTS) and the upper sequence shows mainly by a “stair-stepped” morphology (Stair-  
74   Stepped Sequence; SSS). On the basis of the observations, we defined two regional “discontinuity-  
75   bounded” units in PL, respectively coinciding with RTS and SSS sequences. Our stratigraphic  
76   reconstruction provides new hints on the major scale events that shaped this region. Oscillations in  
77   Martian axial obliquity could have controlled local climate conditions in the past, affecting the PL  
78   geological record.

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85	<b>Keywords</b>
86	Geological processes
87	Mars, polar geology
88	Mars, surface
89	Image processing

## 1. Introduction

The Amazonian South Polar Layered Deposits (SPLD) [e.g., *Herkenhoff and Plaut*, 2000; *Koutnik et al.* 2002] cover most of Planum Australe [*Tanaka and Scott*, 1987] and consist of a up to ~3.7 kilometer-thick stratified sequence (Apl Unit; *Tanaka and Kolb* [2001]; *Kolb and Tanaka* [2001]). Their inferred composition of water ice with minor impurities [e.g., *Cutts*, 1973; *Kieffer et al.*, 1976; *Thomas et al.*, 1992; *Mellon*, 1996; *Clifford et al.*, 2000] has been indirectly verified by Martian subsurface radar sounders [*Nunes and Phillips*, 2006; *Plaut et al.*, 2007] and by density considerations derived from analysis of gravity anomalies associated with Planum Australe [*Zuber et al.*, 2007; *Wieczorek*, 2008; *Li et al.*, 2012]. Both sets of studies estimate upper limits of the volume fraction of sediments of 10%-15%. Subsurface deposit of CO<sub>2</sub> ice [*Phillips et al.*, 2011] and possibly of CO<sub>2</sub> clathrate hydrates (e.g., *Kolb and Tanaka* [2000], *Kargel and Tanaka* [2002], *Wieczorek* [2008]) was hypothesized in the SPLD. Compositional variations have been also suggested by the structural and rheological analysis of deformational systems observed within the SPLD in the PL region, which is again consistent with potentially interbedded layers of CO<sub>2</sub> or CO<sub>2</sub> clathrate hydrates [*Guallini et al.*, 2012].

The inner, thickest portion of the SPLD reaches ~3-4 km in thickness [*Plaut et al.*, 2007; *Byrne*, 2009]. The layered deposits decrease in elevation and thickness toward the ice-dome margins, where lower-relief plateaus are located (i.e., lingulae or lobes). These plateaus (i.e., Australe Lingula (AL), Promethei Lingula (PL) and Ultima Lingula (UL)) are dissected and separated by the recent development of reentrant canyons (e.g. Promethei Chasma (PC), Ultima Chasma (UC) and Chasma Australe (CA); [*Byrne and Ivanov*, 2004]), which are hypothesized to have been formed by katabatic wind scouring and ablation [e.g., *Kolb and Tanaka*, 2001; *Tanaka et al.*, 2008; *Warner and Farmer*, 2008] or by catastrophic outflow of meltwater (jökulhlaup-like discharges; e.g., *Clifford* [1987]; *Anguita et al.* [2000]).

Several authors have used images and radargrams to study the regional SPLD stratigraphy and have described major stratigraphic successions that define distinct units [e.g., *Byrne and Ivanov*,

2004; *Kolb and Tanaka*, 2001, 2006; *Milkovich and Plaut*, 2008]. As concluded in previous studies, the overall depositional history of the SPLD, especially along their margins, has been irregular in time and space. In particular, like in the North Polar Layered Deposits (NPLD), stratigraphic unconformities between the SPLD sequences are locally exposed (i.e. irregularly distributed), suggesting a discontinuous depositional record over time [*Malin and Edgett*, 2001; *Kolb and Tanaka*, 2006; *Seu et al.*, 2007; *Milkovich and Plaut*, 2008; *Milkovich et al.*, 2009; *Guallini et al.*, 2010]. The unconformities, together with the variable ice and dust contents of different layers, are considered to represent past climatic variations [e.g., *Toon et al.*, 1980], occurred in response to significant quasi-periodic changes in the Martian orbital parameters [*Cutts and Lewis*, 1982; *Thomas et al.*, 1992], similar to terrestrial Milanković cycles. In particular, spectral analyses of the PLD with depth (mainly of the NPLD; e.g., *Milkovich and Head* [2005]) are based on *Laskar et al.* [2002] and agrees with the glacial and interglacial ages reconstructed by *Head et al.* [2003]. However, this methodology is still debated because necessitate major assumptions and hypotheses [e.g., *Perron and Huybers*, 2009], especially regarding the SPLD.

This work focuses on a new definition of the regional stratigraphy of PL (Fig. 1a-c; latitude  $\sim 70^{\circ}$ - $80^{\circ}$  S; longitude  $\sim 90^{\circ}$ - $160^{\circ}$  E). The study site has been chosen because 1) it consists of well exposed and laterally continuous SPLD sequences; 2) there is a good dataset coverage. According to MARSIS radar data analyzed by *Plaut et al.* [2007], the present-day thickness of the SPLD sequence in PL (which overlaps the Noachian and Hesperian bedrock units [*Kolb and Tanaka*, 2006]) is comprised between  $\sim 500$  and  $\sim 2500$  m ( $\pm 200$  m of vertical uncertainty).

## 1.2 Background

### 1.2.1 Definition of the stratigraphic units

The limits of remote sensing analysis, the absence (or undiscovered presence) of fossils on Mars, the icy bulk composition of the SPLD (i.e., they are not rocks in the strict sense) and the poor constraints of their physical and chemical properties prevent the use of most of the usual terrestrial

143 stratigraphic methodologies (e.g., lithostratigraphy, biostratigraphy, etc.) to understand the  
144 stratigraphy of the SPLD. On the other hand, stratigraphic reconstructions based on observable  
145 surface texture, erosional style and brightness of the sequences have been previously attempted  
146 [e.g., *Byrne and Ivanov*, 2004; *Milkovich and Plaut*, 2008]. However, this approach can be affected  
147 by incorrect interpretations or uncertainties due to potential similarities between different layers in  
148 different sequences, to variations in local topography (surface slope and orientation), to diverse  
149 illumination conditions, to the presence of dust mantling or seasonal frost, to the use of visible  
150 images with different resolution, to the scale of observation, and to the considered layers properties  
151 [e.g., *Herkenhoff and Murray*, 1990; *Herkenhoff et al.*, 2007; *Fishbaugh et al.*, 2008; *Fishbaugh et*  
152 *al.*, 2010]. All these elements, in general, have a significant influence on the appearance of the  
153 layers in terms of brightness and texture [*Milkovich and Plaut*, 2008] and hide their real bulk  
154 properties, often precluding the possibility of correlation among different sections.

155 In addition to optical images, subsurface radar instruments have been previously used as  
156 complement to outcrop-based studies. In particular, radargrams have been analyzed to identify  
157 interfaces (i.e. the internal stratigraphy) within the SPLD [e.g., *Milkovich and Plaut*, 2008],  
158 overcoming the limitations of visible exposures. However, radar reflectors may not be always  
159 mapped or associated with real subsurface layering. In fact, bad correlations can be due to  
160 subsurface off-nadir reflections (i.e., clutter) or multiple reflections [e.g., *Nunes and Phillips*, 2006;  
161 *Plaut et al.*, 2007; *Christian et al.*, 2013], to conductivity/density variations at depth [e.g., *Reeh et*  
162 *al.*, 1991; *Dowdeswell and Evans*, 2004] and to the different resolution of the dataset [*Nunes and*  
163 *Phillips*, 2006; *Fishbaugh et al.*, 2008; *Christian et al.*, 2013]. Furthermore, and on the contrary  
164 than on the Earth, where it is possible to interpolate other kinds of measurements from ice cores  
165 [*Eisen et al.*, 2003], correlation between radar and visible layering on Mars it is complicated: 1) By  
166 the absence of unambiguous constraints about the SPLD stratigraphy, chemistry and dust  
167 distribution [*Milkovich et al.*, 2009]; 2) Because it is currently unknown what causes reflectors  
168 exactly [e.g., *Lalich and Holt*, 2016]. Finally, in several cases, SPLD radargrams are also



169 characterized by wide no-signal zones defined as “Reflection Free Zones” [*Phillips et al.*, 2011],  
170 which may be caused by successions of layers with low dielectric contrast [*Grima et al.*, 2011].  
171

### 172 **1.2.2. Study aims**

173 To try to avoid all the problematics related to the previous considerations, the present study  
174 relates to the “discontinuity-bounded” classification or “allostratigraphy” [*Chang*, 1975; *Salvador*,  
175 1987] principles. Units are defined making use of surfaces (instead of strata) interrupting the  
176 continuity of the sequences of layers and recording events that interrupted the deposition. In fact,  
177 according to the conventional stratigraphy on Earth [*Salvador*, 1987]:

178 1) Discontinuities mark a stratigraphic contact [e.g., *Bates and Jackson*, 1987] and can be used  
179 to designate a stratigraphic unit (i.e., a mappable body of rock) [*Sloss et al.*, 1949; *Catuneanu*,  
180 2006];

181 2) Discontinuities divide the geologic record into genetically related packages of strata (units)  
182 and can be used for stratigraphic correlation [e.g., *Sloss*, 1963; *Wheeler*, 1964; *Catuneanu*, 2006].

183 These discontinuities are mappable lithological contacts with or without a stratigraphic hiatus or  
184 erosion [*Catuneanu*, 2006], thus including both unconformities and conformities [*Mitchum*, 1977].  
185 The definition of the discontinuity-bounded sequences is irrespective of their eventual  
186 morphological or lithological lateral changes in the depositional environment [*Catuneanu*, 2006].

187 Based on above mentioned principles, the use of discontinuities can minimize most of the  
188 ambiguities derived from the lonely use of the morphologic aspect of the SPLD sequences and of  
189 marker layers [e.g., *Byrne and Ivanov*, 2004; *Milkovich and Plaut*, 2008]. In particular, we used  
190 observed or inferred stratigraphic discontinuities (both along the marginal scarps and in the  
191 subsurface of PL) to define the regional stratigraphy of the SPLD. In fact, it is well known that the  
192 SPLD are characterized by discontinuities: *Kolb and Tanaka* [2006] first reported angular  
193 unconformities in PL using Thermal Emission Imaging System (THEMIS) visible images  
194 [*Christensen et al.*, 2004]. At the same time, buried unconformities have been observed in

195 radargrams [*Seu et al.*, 2007; *Milkovich et al.* 2009].

196 Unconformities are important markers of the deposition/erosion of the Polar Layered Deposits  
197 in both hemispheres, in turn related to global or regional climate changes [*Fishbaugh et al.*, 2008].  
198 Such climate changes are thought to have been induced by variations in Mars orbital parameters,  
199 especially its spin axis obliquity [*Levrard et al.*, 2007; *Greve et al.*, 2010; *Forget et al.*, 2017 in  
200 press]. Even if we can only speculate about the variations of the mean obliquity at the time of the  
201 formation of the SPLD [*Laskar et al.*, 2004], studying the unique SPLD stratigraphy using  
202 discontinuities might enable us to constrain the obliquity history of Mars and to refine the  
203 understating of climate changes during the Late Amazonian.

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### 205 **1.2.3. Used terminology and definitions**

206 The “discontinuity-bounded” classification assumes that:

- 207 1) A "conformity" is a true discontinuity that marks no interruption in the sequence of beds;
- 208 2) An “unconformity” is a true discontinuity that marks interruption in the sequence of beds.
- 209 3) Within the same sedimentary environment, each unconformity can be correlated in  
210 continuity (or not) with the laterally equivalent correlative conformity [*Mitchum*, 1977;  
211 *Posamentier et al.*, 1988; *Van Wagoner*, 1995]. This technique is commonly used on Earth: through  
212 these surfaces, the sequence boundaries can be extended from the observed unconformities across  
213 an entire sedimentary environment, allowing the construction of cross sections and thus of the  
214 regional stratigraphy of a sedimentary body [*Catuneanu*, 2006].

215 On the basis of the above-mentioned principles, in the present paper we refer to:

- 216 1) An “angular unconformity” (AU) when there is an observable unconformity (commonly an  
217 erosional surface showing abrupt layers truncation) between two rock sequences whose bedding  
218 planes are not parallel [*Bates and Jackson*, 1987]. We follow the established practice in planetary  
219 remote mapping of using the definition of angular unconformity independently of the geological  
220 factors causing the inclination of the SPLD layers;

221 2) A “correlative discontinuity” (CD) when it is possible to correlate one or more observed  
222 angular unconformities bounding the same sequence(s) across a broad region (i.e. same depositional  
223 basin) [Mitchum, 1977]. It is assumed that a) the correlative discontinuity is located in the same  
224 elevation range of the observed angular unconformities, b) the correlative discontinuity and the  
225 angular unconformities formed under the same controlling factors [Mitchum, 1977; Catuneanu,  
226 2006]. Thus, the correlative discontinuity is mapped in lateral continuity with the local angular  
227 unconformities, following the inferred stratigraphic position of the angular unconformity.

228 3) A “correlative conformity” (CC) when it is possible to correlate one or more observed  
229 angular unconformities bounding the same sequence(s) across a broad region (i.e. same depositional  
230 basin) [Mitchum, 1977] but not in lateral continuity with the angular unconformities. It is assumed  
231 that the correlative conformity a) can be affected or not by erosion or a depositional hiatus (the use  
232 of correlative continuities is irrespective of the nature of the surface itself [e.g., Catuneanu, 2006]),  
233 b) is in the same elevation range of the mapped angular unconformities. In other words, the angular  
234 unconformities and correlative conformities with the same elevation range and separating the same  
235 sequences can be correlated [Catuneanu, 2006].

236 4) A “discontinuity” (Dis) when we generically speak of a stratigraphic contact between two  
237 sequences.

238 For simplicity and clarity, independent of their nature, all bounding surfaces that can be  
239 regionally correlated (through conformities and discontinuities) with exposed angular  
240 unconformities (AU) and inferred to have been formed under the same controlling factors are  
241 named “AUR<sub>n</sub>”, where “R” stands for regional and “n” is a chronological number that is a function  
242 of the stratigraphic position of the regional discontinuity.

243

#### 244 **1.2.4. Dataset**

245 The region has been analyzed using high-resolution images derived from the Context camera  
246 (CTX, 6.0 m/pix; Malin *et al.* [2007]) and the High Resolution Imaging Science Experiment camera

247 (HiRISE, 0.25-0.32 m/pix; *McEwen et al.* [2007]), both onboard the NASA Mars Reconnaissance  
248 Orbiter (MRO). Although the studied images (approximately one hundred) do not completely cover  
249 the PL area, the spatial resolution of the dataset is sufficient to resolve the structures in detail. In  
250 particular, the high resolution of the CTX and HiRISE images allow us to better exclude false  
251 angular unconformities due to optical effects (i.e., apparent angles) [*Fishbaugh et al.*, 2008] or  
252 created by complex topography (e.g., slope breaks within the sequence, scarps crosscutting layers,  
253 etc.). In some cases, when CTX and HiRISE data were not available, Mars Express High  
254 Resolution Stereo Camera (HRSC) Level-3 (nd3) images (nadir channel, 12.5, 25.0 and 50 m/pix of  
255 spatial resolution) were used [*Neukum et al.*, 2004; *Gwinner et al.*, 2010].

256 The topographic base map was obtained from the Mars Orbiter Laser Altimeter (MOLA) Digital  
257 Elevation Model (DEM) sampled on a 512 pix/degree grid, equivalent to a spatial resolution of  
258 ~115 m at polar latitudes [*Smith et al.*, 2001].

259 The optical and topographic dataset was processed using the USGS Integrated Software for  
260 Imager and Spectrometers (ISIS 3) and analyzed using ESRI ArcGIS. Raster images were draped  
261 onto MOLA Digital Terrain Model using ESRI ArcScene to obtain three-dimensional views.  
262 Images were processed in a polar stereographic projection. For each image, coordinates are given in  
263 decimal degrees (longitude domain -180°/180°, positive east). When possible, only images acquired  
264 during Ls ~230°-260° (southern late spring), Ls ~270°-350° (southern summer) and Ls ~0°-30°  
265 (southern early autumn) were selected because of the absence or reduction of CO<sub>2</sub> ice, which  
266 condenses on the surface of the layers during the cold seasons.

267 The interior of the SPLD has been analyzed using Italian RDR SHARAD data [*Seu et al.*,  
268 2007], converted to raster format and manually mapping reflectors/bounding surfaces using  
269 graphical programs. In total, about 600 radargrams have been analyzed. The sounding radar  
270 operates at a central frequency of 20 MHz (10 MHz of bandwidth) and has a theoretical vertical  
271 resolution of ~15 m in free space [*Seu et al.*, 2007; *Plaut et al.*, 2007] (~10 to 20 m in PLD [e.g.  
272 *Nunes*, 2006; *Nunes*, 2011; *Lalich and Holt*, 2016]), an along-track resolution of approximately 0.3 -

273 1.0 km and a cross-track resolution of approximately 3 - 6 km.

274 We selected representative profiles for the analysis (Fig. 1a). In the radargrams, the vertical axis  
275 represents the two-way travel time in microseconds and is converted to depth using a dielectric  
276 constant of 3.4, which is consistent with a mixture of 90% water ice and 10% basaltic impurities  
277 [e.g. *Heggy et al.*, 2007; *Plaut et al.*, 2007; *Seu et al.*, 2007]. This value is used only below the  
278 reflection corresponding to the SPLD surface.

279 As previously cited, the interpretation of the reflectors in the SPLD are often uncertain because  
280 of strong surface/subsurface clutter. Thus, used radar tracks were simulated using algorithms  
281 developed by the Italian SHARAD team to identify the most important clutter [e.g., *Russo et al.*,  
282 2008].

283

## 284 **2. Results**

### 285 **2.1. Description of the discontinuities in images**

286 On the basis of the areal coverage of the images dataset, several stratigraphic sections (or logs;  
287 L1-L21 in Fig. 1a and Table 1) of interest have been identified along the walls of marginal  
288 erosional scarps of PL and of the chasmata, troughs and reentrants.

289 Some exposures clearly show sequences interrupted by angular unconformities (see Fig. 1a for  
290 location), which can in turn be correlated with correlative discontinuities or conformities. The  
291 angular unconformities (cf. Figs. 2-4 and A1-A3) are located in the SPLD sequence between a  
292 minimum of ~1400 m and a maximum of ~2500 m (average of ~1800-1900 m) in MOLA height. In  
293 most of the cases, these bounding surfaces confine sequences having similar appearance. In general,  
294 the elevations and the lengths of the angular unconformities (which are in some cases traceable over  
295 tens of kilometers; Fig. 1a) are comparable to those observed for angular unconformities in other  
296 locations of the Planum Australe ice dome [e.g., *Kolb and Tanaka*, 2006; *Milkovich and Plaut*,  
297 2008].

298 By applying the geologic V-rule [*Simpson*, 1968; *Meentemeyer and Moody*, 2000] and studying

299 the geometric relationships in plan view between the topographic surface (marked by the elevation  
300 contours) and the locally exposed contour planes of the discontinuities (deduced by their mapped  
301 plan-view traces), we noticed that these contour planes are generally curved lineaments  
302 conformable with topographic contours (i.e., they have the same bending polarity). This geometric  
303 arrangement entails planes dipping in the same direction as the slope (i.e., toward the SPLD  
304 margins), but with a shallower dip angle (in general,  $< 1^\circ$ ).

305 Most representative cases are located in three regions:

306 1) In the first location (Figs. 1a and 2; L7b in Tab. 1) the stratigraphic exposure shows an  
307 angular unconformity located along the PL margin at an average elevation of about 1800 m. The  
308 AU can be followed with quasi-continuity for about 120 km and correlated with correlative  
309 discontinuity/conformity (L7a, c in Tab. 1). The AU separates two distinct morphologic sequences.

310 2) The second angular unconformity (Fig. 3) is exposed along Ultimum Chasma scarps (L18; cf.  
311 Tab. 1) at an average elevation of about 1850 m. The AU can be correlated with a correlative  
312 discontinuity and mapped for about 90 km. It divides two morphologic sequences similar to those  
313 observed in L7.

314 3) Another stratigraphic outcrop showing an angular unconformity is exposed in Promethei  
315 Chasma scarps (L20; Fig. 4 and Tab. 1). The AU is located at an average elevation of about 2150  
316 m and can be correlated with correlative discontinuity for about 60 km. It bounds two morphologic  
317 sequences again similar to those observed in L7 and L18.

318

## 319 **2.2. Description of the discontinuities in radargrams**

320 Angular unconformities can also be identified in some radargrams (tracks from 1 to 27 in Fig.  
321 1a), where the observed reflectors seem to be locally inclined and truncated. In particular, at  
322 different levels of confidence, we observed potential radar unconformities in 28 locations (cf. Table  
323 2). The unconformable surfaces are sub-horizontal, laterally extend up to approximately 100 km on  
324 average and are primarily focused in one broad area of PL (cf. white dotted inset in Fig. 1a), plus

325 other minor and more uncertain regions.

326 The main area characterized by the presence of radar angular unconformities is located in the  
327 middle of the PL, equatorward of the Australi Sulci and poleward of the visible sections L7, L9 and  
328 L10 (where angular unconformities are exposed; 80°S-85°S latitude; 110°E-130°E longitude; Fig.  
329 1a; (1) in Table 2). With respect to the maximum length of the PL ice sheet, several longitudinal  
330 radar profiles (Figs. 5, 6, A4 and A5) display two packs of reflectors with a different dip-angle. In  
331 particular, some of the reflectors (usually the bottom ones) seem to be truncated against others  
332 (usually the top ones) that are continuous, sub-parallel and with a dip toward the PLD margins. The  
333 angle between the two sets of reflectors suggests an unconformable contact between two radar  
334 sequences. This observation is consistent with *Seu et al.* [2007] and *Milkovich et al.* [2009]. The  
335 observed angular unconformities are located at average elevations of ~1900 m. The same structural  
336 configuration – even if subtler – can be detected in data from transverse orbits (e.g., Figs. 7 and A6)  
337 that crosscut the longitudinal orbits. This evidence supports the idea that the observed angular  
338 unconformities are real geologic structures, as previously suggested by some authors (e.g., *Seu et*  
339 *al.* [2007]). The high number of crosscutting radar tracks covering the study area allows us to  
340 interpolate the minimum, intermediate and maximum points of elevation (in terms of latitude,  
341 longitude and depth below the topographic surface) of the angular unconformities observed in each  
342 2D single orbit to obtain a three-dimensional view of the buried unconformable surface (Fig. 8).  
343 The interpolation of sample elevation points has been automatically calculated by using ArcGIS,  
344 adopting Kriging method. This kind of interpolation is a geostatistical technique often used on soils  
345 science and geology, that on the contrary of other tools minimizes the mean square error [e.g.,  
346 *Burrough*, 1986; *Oliver*, 1990]. In this location, the reconstructed buried 3D angular unconformity  
347 is a continuous rough surface with an approximate area of 10,000 km<sup>2</sup> and a slight dip toward the  
348 SE (~0.04°-0.6° dip angle). Its average elevation and dipping direction makes the observed angular  
349 unconformity consistent with the unconformities defined in the visible images.

350 The second location is in the same latitude range as the previous one (80°S-85°S) but between

351 the longitudes of 100°E and 110°E (17, 25, 28 in Fig. 1a; cf. Fig. 9 and location (2) in Table 2).  
352 Two sets of intersecting radargrams show again two groups of (less bright) reflectors that have  
353 different dip angles and appear to be truncated, thus suggesting the presence of an angular  
354 unconformity between them. This latter surface dips toward the PL margins (i.e., to the east) at a  
355 low angle ( $\sim 0.1$ - $0.2^\circ$ ). If the angular unconformity plane were to extend to the PL margin, it would  
356 intersect the topographic surface corresponding to the L7 section at an elevation of approximately  
357 2000 m. This value is again consistent with the local elevation of the angular unconformities  
358 observed in the images.

## 359 360 **2.3. Description of the stratigraphic sequences in the visible images**

361 As aforesaid, the observed discontinuities divide two main stratigraphic sequences within the  
362 SPLD. These sequences, whose most important distinguishing features are highlighted in Figures  
363 10-12, differ in average layer thickness, in morphology, in brightness and in erosional behavior of  
364 the bedding planes. The transition between the two sequences is, in some cases, marked by a slight  
365 break in topographic slope (cf. Fig. 13 as an example) that corresponds to the topographic contour  
366 of the discontinuities. In particular, the basal sequence is characterized by a higher dip angle of the  
367 scarp ( $\sim 5^\circ$  to  $20^\circ$ ) than the top sequence ( $\sim 1^\circ$  to  $10^\circ$ ).

### 368 369 **2.3.1. Ridge and Trough sequence (RTS)**

370 The basal sequence resting below the discontinuities is mainly characterized by a “ridge and  
371 trough” morphology, firstly defined by *Malin and Edgett* [2001] (Figs. 10, 11). On average, the  
372 package of layers is approximately 650-700 m thick. The RTS shows lateral variations in thickness  
373 and textures that may be due to different erosion or deposition rates (cf. Fig. A3a and layer S15 in  
374 Fig. A7).

375 The sequence is mostly characterized by irregularly alternating dark and bright layers that are  
376 generally thin (up to some meters in thickness; Fig. 11a). From their appearance, these layers can be



377 grouped into stratigraphic packs that are clearly distinguishable from adjacent ones (cf. Figs. A7-  
378 A9). In some cases, a further minor-order layering of sub-meter thickness appears at a closer scale  
379 (HiRISE resolution; cf. Fig. 11b).

380 By considering the direction of illumination of the scarp in the images and from HiRISE DTM  
381 (cf. Fig. 14 in *Guallini et al.* [2012]), we observed that dark bedding planes generally show a  
382 typical concave-upward profile (“trough-shaped” morphology; Tr in Fig. 11b) while bright layers  
383 have a convex-upward profile (“ridge-shaped” morphology; Rg in Fig. 11b) [*Malin and Edgett*,  
384 2001]. Thus, the brightness might vary consistently with the morphology and texture of the layers  
385 and could be influenced by the dust content of their bulk composition [e.g., *Squyres*, 1979; *Jakosky*  
386 *et al.*, 1995; *Malin and Edgett*, 2001; *Richardson and Wilson*, 2002; *Haberle et al.*, 2003; *Mischna*  
387 *et al.*, 2003; *Milkovich and Head*, 2005]. In this case, the higher absorption of the solar radiation in  
388 the dark layers, causing their high rate of sublimation (i.e., the relative velocity at which the icy  
389 matrix sublimates), could explain their “trough-shaped” morphology. Vice-versa, the opposite  
390 reasoning can be made for bright layers. On the other hand, another (in our advice) less possible  
391 hypothesis is that “trough-shaped” layers appear darker than the “ridge-shaped” ones because dust  
392 deposited more easily on their hollowed surface. In this last case, the variation of brightness of the  
393 layers would be only apparent and not representative of their bulk composition.

394 At CTX resolution, the surfaces of the bedding planes appear uneven and locally pitted (Fig.  
395 11b, c). This erosional texture varies in intensity from layer to layer and whereas, again, it was  
396 indicative of the real bulk composition of the bedding planes, could change as a function of the  
397 varying mechanical strengths to erosion and the varying rates of sublimation of the layers. In  
398 addition, jagged layer edges (Ne in Fig. 11a) are not uncommonly observed in plan view. They  
399 have an almost regular pattern that may indicate a pristine structural control (preferential pathways  
400 of fracturing) on their erosion [*Guallini et al.*, 2012].

401 The vertical variation of layer thickness along the RTS sequence appears to be irregular (as  
402 observed by *Limaye et al.* [2012] at other SPLD sites). Thus, a specific thickening gradation is not

403 clearly identifiable.

404 The RTS sequence is occasionally interrupted by single or limited groups of “bench-like”  
405 bedding planes, typically of sub-decameter thickness (Bn in Fig. 11). These layers, which are  
406 prevalent in the upper sequence, are characterized by an irregular erosional pattern on their surfaces  
407 and by notched edges, which are sometimes clearly marked. They are locally more common in  
408 topographically higher observed outcrops.

409

### 410 **2.3.2. Stair-Stepped sequence (SSS)**

411 The sequence resting upon the discontinuities is characterized by a “stair-stepped” morphology  
412 [Malin and Edgett, 2001], marked by a regular and clear bench-like morphology (Figs. 10, 12). The  
413 sequence has a maximum thickness of ~700 m, but this may be an underestimate because the  
414 elevation of its basal surface is uncertain in some places.

415 In general, the layers and layer packs are up to decametric in thickness and lack significant  
416 brightness variations. They mostly appear medium-dark toned, possibly because of dust mantling.  
417 The surfaces of the layers generally show an uneven and pitted erosional pattern (see layer surfaces  
418 in Fig. 12). However, it is not clear if this texture is linked to an inner property of the bulk  
419 composition of the bedding planes or to the overlying dust deposit. The edges of these strata are  
420 often notched (Ne in Fig. 12).

421 In addition to the dominant “stair-stepped” characteristic of the sequence, several variations in  
422 stratigraphy are present. For example, some SSS outcrops show a “ridge and trough” morphology in  
423 some layer packs in Chasma Australe, which is more similar to the RTS (see L18-L20 in Figs. 3-4  
424 and Fig. 14). The “ridge and trough” sub-sequences are mainly exposed toward the base of the SSS  
425 sequence, close to the discontinuity surfaces, which may suggest a local progressive transition from  
426 the RTS.

427

### 428 **2.3.3. Minor-order morphostratigraphic sequences**

429 Within the major-order stratigraphic sequences (i.e., RTS and SSS), it is possible to observe  
430 several minor-order “morpho-sequences” in layer blocks showing similar morphologies and  
431 possible vertical repetition along the exposure (cfr. Fig. A10 and Tables A1-A3). The differences  
432 between these possible minor-order sequences are in terms of number of layers, stratigraphic  
433 location and texture. In addition, in most cases, sub-sequences present in one exposure are  
434 completely absent in others: they lack regional continuity, as occasional exposure of lateral pinch-  
435 out terminations of the layers also suggests (cf. S15 and Fig. A7). It follows that, within the RTS  
436 and SSS sequences, each analyzed outcrop shows minor-order packs of layers that can be correlated  
437 across the PL only with difficulty, which may outline local independent events superimposed on  
438 regional ones. However, according to the stated stratigraphic approach, although the presence of  
439 minor-order sequences certainly implies greater complexity in the SPLD stratigraphy, we chose to  
440 limit our analysis to the regional events.

#### 441 442 **2.4. Brief description of the stratigraphic sequences in radargrams**

443 Based on observation of the unconformities in the radargrams, two SPLD radar sequences that  
444 occasionally intersect the PL topographic surface can be defined. The transition between the two  
445 sequences is in some cases marked by low intensity reflections zones ~100 m thick that rests upon  
446 the unconformities when present (letter A in Figs. 5, 6 for location).

447 Although the appearance of the two bounded sequences is generally very similar when  
448 examined at radar wavelengths, at the PL margins it is possible to observe some variations: 1) the  
449 upper sequence is thinner than the bottom one; 2) the reflectors of the two radar sequences both dip  
450 slightly toward the PL margins but have different (apparent, due to view geometry) dip angles  
451 (~1.5° upper sequence vs. ~0.1° bottom sequence; cf. Fig. 6 for example); and 3) reflectors are  
452 lower in number or locally absent in the top portion of the upper sequence. All these elements agree  
453 with the observations in the visible images and the two radar sequences seem to represent the same  
454 stratigraphy of the RTS and SSS.

455

### 456 3. Discussion

#### 457 3.1. Definition of the regional discontinuity “AUR1”

458 The observed unconformable surfaces are not continuously exposed across the PL margins. This  
459 implies some uncertainties in their stratigraphic positions and thus their correlation. On the other  
460 hand, their exposure in various places suggests their presence at regional scale in PL. Also, despite  
461 the elevation of the exposed unconformities is not constant from section to section (it generally  
462 decreases toward the PL margins), at the regional scale several do not show significant variations in  
463 topographic heights (comprised between  $\sim 1900 \pm 100$  m in average; Fig. 15 and Tab.1).

464 All these angular unconformities divide the RTS and SSS sequences. Around the PL margins  
465 and also along the scarps of PC, UC and CA, these unconformities can be correlated through  
466 correlative discontinuities and conformities (the most significant examples are reported in Figs. 2,  
467 4, 5). We speculate that these unconformities originated under the same erosional or non-  
468 depositional event. As a result, we assume that all these local discontinuities (unconformable and  
469 conformable) can be related to one regional discontinuity surface, appointed as AUR1 (Figs. 2-5  
470 and Tab. 1).

471 The local differences in elevation of the unconformities can be explained as following:

472 1) They are a unique and continuous surface but the erosion rate could have varied spatially in  
473 PL as a function of the existing local factors (i.e., narrow-scale topography, layer consistency, etc.)  
474 and resulted in both unconformable and conformable surfaces. As instance, it is possible that, in  
475 some locations, depositional lag formed in place of the angular unconformities [e.g., *Fishbaugh et*  
476 *al.*, 2008; *Byrne*, 2009].

477 2) They are a unique and almost continuous regional surface that is topographically irregular.  
478 Assuming this case, it is possible to calculate that the regional surface plane has a gentle slope of  
479  $\sim 0.05^\circ$  along the NS sections and  $\sim 0.1^\circ$  along the EW sections (cf. Fig. 1a), dipping toward the PL  
480 margins. This attitude is consistent with that derived from the radargrams (cf. Section 2.2). It is also

481 consistent with *Byrne and Ivanov* [2004], calculating a slight dip angle of the SPLD toward the  
482 periphery of the ice dome, progressively flattening toward its margins. In this sense, the gentle dip  
483 of the regional discontinuity supports the hypotheses that the deposition rate of the RTS may have  
484 been slightly greater near the center of PL and/or that the erosional rate of the same sequence was  
485 slightly greater near the margins of PL.

486 At the same time, angular unconformities seem to be present also in the buried portion of the  
487 SPLD in PL (cf. Figs. 5-9). This suggests that a large area around the PL and beyond the marginal  
488 scarps of the region has undergone erosion or non-deposition. The radar unconformities have an  
489 elevation range (about 1900-2000 m) consistent with the elevation of the similar structures exposed  
490 on the PL margins. Thus, we infer that also the buried angular unconformities are consistent with  
491 the AUR1.

492 Based on the analysis of *Kolb and Tanaka* [2006], the AUR1 should be older than a higher  
493 regional discontinuity located at the base of a third most recent SPLD sequence (i.e., Aa2 unit).  
494 This discontinuity can be inferred in some peripheral outcrops of PL [*Kolb and Tanaka*, 2006],  
495 close to the poleward borders of Promethei Chasma and Chasma Australe (in L2, L5, L17, L18,  
496 L20 logs; Fig. A11), where there is a local increase in the thickness of the SPLD (Fig. 1a, c).  
497 Nevertheless, this bounding surface, located at a presumed elevation >2300 m, has not clearly been  
498 observed in the analyzed region. One possible exception is in one marginal outcrop (e.g., L2; cf.  
499 Table 1) in which it cannot be distinguished with confidence due to limitations (in terms of  
500 quality/resolution and areal coverage) of the dataset. On the contrary, this structure has not been  
501 observed in radargrams because the rough topography of the likely region in which it is supposed to  
502 be would prevent SHARAD to see eventual reflectors. We appointed this uncertain discontinuity as  
503 AUR2.

504 The local observed unconformities at lower (~1400 m; AUL1; cf. Table 1 and Fig. A1) and  
505 higher (~2300 m; AUL2; cf. Table 1 and Fig. A1) elevations than the AUR1 are apparently  
506 unrelated to this latter and the AUR2 regional surfaces. These unconformities (for the most

uncertain) seem to bound sequences of minor-order rank without lateral continuity at regional scale. Although they should imply a further complexity of the SPLD stratigraphy, given their uncertainty and absence of lateral continuity, they do not allow the definition of minor-order discontinuity-bounded sequences [e.g., *Chang*, 1975]. Thus, they were not considered in the definition of the regional stratigraphy of PL.

### 3.2. Definition of the “AUR1-bounded” units and regional stratigraphy of PL.

Based on the previous observations and assumptions we can define two formal regional “discontinuity-bounded” units or Synthems in the SPLD in PL (Fig. 15). These units are separated by the AUR1 discontinuity and are named, respectively:

- 1) Promethei Lingula 1 unit (PL1), coinciding with the RTS morphologic sequence;
- 2) Promethei Lingula 2 unit (PL2), coinciding with the SSS morphologic sequence.

Based on the available dataset and the good exposure of the layers, the stratigraphic sequence L7b (Figs. 1a, 10-12) is assumed to be representative of the regional PL stratigraphy and was thus chosen as a type section. This section best preserves the layered stack and acts as reference point for analyzing the regional stratigraphy and for comparing and correlating the exposed sections across the region. It is located in the northeastern margins of PL (latitude 79.31°S, longitude 102.23°E; cf. Figs. 1a and Table 1).

The regional stratigraphy of PL is obtained correlating across the PL region the L7b with the other sections through the defined AUR1 discontinuities. The lower, older PL1 unit (Fig. 15) is exposed only along the PL scarps. It is confined at its bottom by an inferable non-conformity surface with the Late Noachian and Hesperian bedrock [*Tanaka et al.* 2014] and at its top by the AUR1 discontinuity. The PL1 is characterized by a maximum thickness of ~800-1000 m and is located in the vicinity of Promethei Chasma (L20, Fig. 15) in the inland PL and along some sectors of the PL margins, primarily corresponding to the L7 section (Fig. 15). Following the AUR1 elevation trend, the PL1 thickness significantly decreases toward the margins of the ice sheet, where

533 erosion was focused, to a minimum of 250 m measured in the L6 section. This unit is consistent  
534 with the Aa1a member of *Kolb and Tanaka* [2006], observed by them only in Promethei and  
535 Ultimum Chasmata.

536 The PL2 (Fig. 15) is confined at its bottom by the AUR1 discontinuity and at its top by the  
537 topographic surface or, possibly, by the AUR2 discontinuity. The PL2 is consistent with the locally  
538 observed Aa1b member of *Kolb and Tanaka* [2006]. The possible different attitudes of the bedding  
539 planes of the two units in both visible and radar images demonstrate that the PL2 was deposited  
540 atop the irregular upper surface of the PL1. The unit PL2 may reach a maximum thickness of ~900-  
541 1000 m (L17). Unlike for the PL1, the logs indicate that thicker sequences are primarily located  
542 near the PL margins (i.e., L5, L9, L10, L17, L18). Again, this may be because after the PL2  
543 deposition and during the formation of Australi Sulci by wind ablation [*Kolb and Tanaka*, 2006],  
544 erosion was primarily focused on the central parts of the PL and removed part of the PL2 after its  
545 deposition. It is also possible that the PL2 deposition was not homogeneous over PL and was  
546 instead focused, for some unknown reason, on its margins. This last interpretation could be  
547 suggested by radargrams, in which more net accumulation (sum of net deposition and erosion)  
548 seems to have occurred on the sides of PL (e.g. ESE side in Fig. 9).

549 According to *Kolb and Tanaka* [2006], a further unit (Aa2) could unconformably overlie the  
550 PL2 in the Promethei and Ultimum Chasmata region (logs L17, L18, L20), near the Australi Sulci  
551 and on the poleward side of the Chasma Australe (log L5), separated by the AUR2. Thus, PL region  
552 has been only marginally interested by youngest depositional events. Alternatively, the absence of  
553 the Aa2 in the strict PL lobe suggests its complete removal by erosion or non-deposition. Moving  
554 from the PL inland (A-A' profile) toward the PL margins (B-B' profile) in Fig. 15, the average  
555 thickness of the SPLD sequence decreases from approximately 1700 m to approximately 1200 m.  
556 This can be explained through some combination of the following:

557 1) The ice-dome physiography, which is usually characterized by a depositional rate higher at  
558 its center (“accumulation-like zone”) than at its margins (“ablation-like zone”). This would explain

559 the slight dip angle at the regional scale of the SPLD toward the periphery of the ice dome, as stated  
560 by *Byrne and Ivanov* [2004] and suggested by the radargrams;

561 2) The presence, toward the central ice dome, of the overlying unit Aa2, according to mapping  
562 done by *Kolb and Tanaka* [2006];

563 3) The heterogeneous erosion of the SPLD unit, primarily focused along the PL margins. This  
564 trend is reversed in the Australe Sulci region (EW profile), where the average thickness of the  
565 SPLD sequence is lower than in the PL margins. This is consistent with a high rate of erosion in the  
566 region due to katabatic winds, as suggested by *Koutnik et al.* [2005] and *Kolb and Tanaka* [2006].  
567

### 568 **3.3. Some possible climatic implications**

569 As introduced in Section 1, unconformities are important markers of the growth and retreat of  
570 the Polar Layered Deposits in both hemispheres. They indicate that global or regional climate  
571 changes affected Mars at various times in its recent history [*Fishbaugh et al.*, 2008], likely induced  
572 by variations in Mars orbital parameters, in particular its spin axis obliquity [*Levrard et al.*, 2007;  
573 *Greve et al.*, 2010; *Forget et al.*, in press, 2017]. Mars's obliquity indeed varies by about  $\pm 10^\circ$  with  
574 a  $10^5$  year cycle, around a mean value (currently  $25^\circ$ ) which is thought to have changed by several  
575 tens of degree in the past [*Laskar and Robutel*, 1993; *Touma and Wisdom*, 1993; *Laskar et al.*,  
576 2004]. The resulting climate changes were studied by *Toon et al.* [1980] and *Jakosky and Carr*  
577 [1985] on the basis of energy balance calculations, and explored in more details by numerical  
578 global climate models able to simulate Mars water cycle [*Mischna et al.*, 2003; *Levrard et al.*, 2004;  
579 *Montmessin et al.*, 2005; *Forget et al.*, 2006; *Levrard et al.*, 2007; *Madeleine et al.*, 2014]. These  
580 studies demonstrated that, while surface water ice is only stable in the polar regions on present-day  
581 Mars, large amount of water ice could have accumulated at lower latitudes at the expense of the  
582 polar reservoirs when the obliquity was higher, forming all sorts of glaciers-related landforms and  
583 ice mantles, which remnants can still be observed today. To first order, the ice-rich strata of the  
584 Polar Layered Deposits result from the accumulation of ice in the polar regions when the climate



585 conditions (low mean obliquity) favored ice accumulation in the polar regions, while  
586 unconformities corresponds to periods of net ice sublimation at the poles, resulting in the formation  
587 of irregular erosion.

588 In the Northern hemisphere, several studies have linked the stratigraphy observed in surface  
589 images [e.g. *Laskar et al.*, 2002; *Levrard et al.*, 2007; *Hvidberg et al.*, 2012] and radargrams [e.g.  
590 *Putzig et al.*, 2009] with the variations of Mars' obliquity and orbital parameters calculated for the  
591 past 5 million year. Before ~5 Ma, the mean obliquity was higher than today and its values  
592 oscillated between 25° and 45° [e.g. *Laskar et al.*, 2002; 2004]. In such conditions, climate models  
593 predict that the ice-rich NPLD could not persist stably at the surface and that they slowly  
594 accumulated after 4 million years ago [*Levrard et al.*, 2007; *Greve et al.*, 2010] when the mean  
595 obliquity decreased. While the details of the stratigraphy are not yet fully understood, *Levrard et al.*  
596 [2007]'s model was recently found to successfully predict the upper 300 m of the NPLD cap (and  
597 the major discontinuity below), thought to have accumulated since ~370,000 years ago [*Smith et al.*,  
598 2016].

599 Compared to the NPLD, the Southern Polar Layered Deposits are more difficult to understand  
600 for two reasons:

601 1) According to the cratering record, the age of the SPLD surface ranges between ~30 to 100  
602 Myr [*Plaut et al.*, 1988; *Herkenhoff and Plaut*, 2000; *Koutnik et al.*, 2002]. Thus, they accumulated  
603 during periods for which no orbital and obliquity data are available, because of the inherent chaotic  
604 nature of the evolution of the Martian obliquity [e.g., *Laskar et al.*, 2004]. Chaos prevent the  
605 extrapolation of the Martian spin/orbit history before ~10-20 My ago [*Laskar and Robute*, 1993;  
606 *Touma and Wisdom*, 1993]. Thus, we can only speculate about the variations of the mean obliquity  
607 at the time of the formation of the SPLD, guided by the statistical studies performed by *Laskar et*  
608 *al.* [2004]. In fact, studying the stratigraphy of the SPLD might ultimately enable us to  
609 observationally constrain the obliquity history.

610 2) According to models, the Mars climate system tends to favor the accumulation of water ice in

611 the Northern Polar Regions rather than in the South, because of the topographic asymmetry  
612 between the Southern and Northern hemisphere. The global north-south elevation difference favors  
613 a dominant southern summer Hadley circulation (responsible for the inter-hemispheric transport of  
614 water) [Richardson and Wilson, 2002b] and may also prevent the formation of a Northern “dusty  
615 season” and the related atmospheric warming when the perihelion was opposite of today (i.e. during  
616 Northern winter; Montmessin *et al.* [2005]). Admittedly, Montmessin *et al.* [2005] showed that  
617 every 50 000 years there are periods when Mars eccentricity permit the accumulation of ice in the  
618 Southern Polar regions at the expense of the NPLD. This is when Mars perihelion occurs during  
619 Northern summer (the opposite of today's conditions), resulting in a more intense sublimation of the  
620 NPLD due to increased insolation. However, the amount of ice then accumulated in the southern  
621 polar region should only reach a few meters at most [Montmessin *et al.*, 2005]. On average, the  
622 present-day Mars climate system seems to only allow the formation of thick Polar Layered deposits  
623 in the North. This explains why the NPLD are much more recent than the SPLD, but raises a  
624 question: in which conditions did ice accumulate at the South Pole to form the 3 km-thick SPLD?

625 A first possibility could be that, when the SPLD formed, the atmospheric pressure was  
626 significantly higher than today. With a thick enough atmosphere, atmospheric adiabatic cooling can  
627 influence the surface and near-surface temperature and favor ice accumulation in the high altitude  
628 south polar region rather the northern plain, just like on Earth today. This process was invoked to  
629 explain the origin of the Dorsa Argentea Formation, a Hesperian southern polar ice cap now buried  
630 by sediments [Wordsworth *et al.*, 2013]. On present-day Mars, the atmosphere is too thin to affect  
631 the surface temperature and the local topography has no significant effect on surface temperature  
632 Forget *et al.* [2013]. The transition between a “present-day Mars regime” and an “Earth-like  
633 regime” was investigated by Forget *et al.* [2013], who showed that at least 100 mbar is needed to  
634 affect surface temperatures and thus ice stability. This is probably unlikely for Mars in the past 200  
635 Millions years [Forget *et al.*, 2017 in press].

636 A more likely possibility is that the Southern Polar Layered Deposits formed during periods

637 when the water cycle was so important that ice accumulated in both the northern and southern polar  
638 regions. For instance, this could have occurred when large amounts of tropical or mid-latitude water  
639 ice were available to sublime and the obliquity low enough to favor net condensation of water ice at  
640 the poles [Levrard *et al.*, 2004; Madeleine *et al.*, 2009]. From that point of view it is interesting to  
641 note that the largest non-polar glacier related landforms observed on Mars do not date from the past  
642 10 millions of year, but rather seems to have evolved to their present-day aspect 30 to 100 millions  
643 years ago, the approximate age of the SPLD [e.g., Herkenhoff and Plaut, 2000; Koutnik *et al.*  
644 2002]. This includes the Mid-Latitude Lobate Debris Aprons and Lineated Valley Fills, the Mid-  
645 High Latitude Concentric Crater Fill, or the Tropical Mountain Glaciers (see Head and Marchant  
646 [2009]; Forget *et al.* [2017], and reference therein). Another key type of landforms are the mid-  
647 latitudes "pedestal craters" which are impact craters perched on a decameters thick pedestal  
648 interpreted to be the remnant of ice-rich deposit locally armored from erosion by the cratering  
649 event. The presence of thousands of pedestal craters poleward of 30° latitude suggest the presence  
650 of very extensive, decameters thick, water ice deposits covering the mid to high latitudes in the past  
651 [Kadish and Head, 2010]. Kadish and Head [2014] calculated a wide range of crater size-frequency  
652 distribution ages for the formation of the pedestal crater but showed that 70% of the pedestal ages  
653 are less than 250 Myr old. During the 150 Myr period between 25 Ma and 175 Ma, they found at  
654 least one pedestal age every 15Ma.

655 Likely, the SPLD formed on a very ice-rich planet Mars possibly covered by decameters thick  
656 ice deposits overall the mid-latitudes and extensive glaciers in the tropics. They recorded climatic  
657 events from a very different period than the ones archived in the NPLD, although it is not possible  
658 to exclude at all that climate during the formation of the SPLD (about 100 Ma) was similar to  
659 climate 5-0 Ma. In any case, another point of evidence for a very different evolution of the SPLD  
660 compare to the NPLD is the presence of massive deposits of CO<sub>2</sub> ice in the Planum Australe, but  
661 not in the Planum Boreum [Phillips *et al.*, 2011].

662 While it is premature to attribute an absolute age to the recorded events and to quantitatively

663 constrain the obliquity history of Mars, analyzing the stratigraphy of Promethei Lingula allows to  
664 investigate major depositional and erosional events. Moreover, the SPLD are likely much older than  
665 the NPLD and they may represent a unique record not found elsewhere. Thus, as introduced, their  
666 stratigraphy contributes to a more refined understanding of climate change during the Late  
667 Amazonian on Mars. For instance, we can note that the discontinuity AUR1 represents a clear  
668 change in the environmental conditions of PL, interrupting the local continuity in the SPLD  
669 deposition. AUR1 can be related to a primary erosional or non-depositional event (by sublimation,  
670 melting, wind abrasion, and/or the absence or reduction of solid precipitation/condensation) taking  
671 place between two main depositional stages by solid precipitation/condensation and wind  
672 accumulation of the SPLD. Fig. 16 illustrates the overall evolution of the PL region and the  
673 different climatic phases, as described below:

674 Time 0 (Fig. 16a). During a first climatic period, the unit PL1 was deposited and the PL ice-  
675 sheet reached its maximum advance, probably as a result of the instability of large tropical and mid-  
676 latitude ice reservoir at relatively low obliquity.

677 Time 1 (Fig. 16b). During another insolation period (from lower to higher obliquity (E1), a  
678 climatic change began that warmed the polar regions on average. This would have determined an  
679 extensive erosional stage of the PL1 sequence, forming the AUR1. For simplicity, assuming that the  
680 gentle regional dip angle of the AUR1 ( $0.05^{\circ}$ - $0.1^{\circ}$ ) is only due to the inhomogeneous erosion rate  
681 removing the PL1 (and thus also assuming a homogeneous thickness of the PL1 before the AUR1  
682 formation), it is possible to estimate that the possible maximum thickness of material removed  
683 across the length of PL (approximately 350-400 km) was ~300-600m. The warm temperatures at  
684 this time [Constard *et al.*, 2002] may have induced local melting and broad deformation of the  
685 SPLD (wet conditions), which in turn affected the attitude of the layers and possibly triggered or  
686 accelerated an inhomogeneous outward movement of the PL ice sheet [e.g. Guallini *et al.*, 2012;  
687 2014].

688 Time 2 (Fig. 16c). From high to low average obliquity. A new, gradual decrease of the

689 rotational axis to lower angles (D2) brings about a new drop in mean surface temperature at polar  
690 latitudes and, assuming that ice is still available at lower latitudes, the beginning of the deposition  
691 of the unit PL2 upon the PL1. The accumulation of the PL2 followed the existing topography of the  
692 AUR1, resting upon it both with conformable and unconformable contacts.

693 Time 3 (Fig. 16d). From low to high average obliquity. This episode was followed by a period  
694 of erosion of the PL2 (from low to high obliquity; E2), which was likely combined with a reduction  
695 in or absence of precipitation, causing a negative mass balance of the PL ice sheet. Particularly at  
696 the inland PL, close to the high surface topography of the ice dome, katabatic winds removed  
697 material from the SPLD [Koutnik *et al.*; 2005], forming the Australe Sulci [Kolb and Tanaka; 2006]  
698 and removing significant volumes of the PL2. Based on evaluations of the Australe Sulci region  
699 done by Kolb and Tanaka [2006] and the stratigraphic correlation of outcrops along NS and EW  
700 profiles (cf. Fig. 15), up to 300-500 m of the PL2 was possibly removed.

701 Time 4 (Fig. 16e). From high to low average obliquity. During the transition from high  
702 obliquity to the present-day low obliquity, a new depositional stage formed the Aa2 unit [Kolb and  
703 Tanaka; 2006], perhaps mostly outside of PL and divided from the PL2 by the inferred regional  
704 unconformity AUR2. The deposition of the unit occurred at latitudes higher (i.e., ~80° latitude) than  
705 the PL region, which may only have been marginally buried by the Aa2, and was quickly followed  
706 by renewed widespread erosion of the SPLD (E3). According to Koutnik *et al.* [2005] and  
707 Milkovich and Plaut [2008], this latter erosional phase, which is primarily characterized by dry  
708 conditions and dust accumulation, occurred in a climate similar to that of the present day (i.e.,  
709 warmer temperatures are not required). As suggested by the medium-high dip angles of the SPLD  
710 scarps [Milkovich and Plaut; 2008], erosional processes are still ongoing by wind ablation and  
711 sublimation. According to Byrne [2009] and given the uncertainties, we assume that the  
712 preservation of the SPLD through periods of high obliquity could be explained if the sublimation  
713 and melting of water ice is a self-limiting process. In particular, surface dust lag caused by the  
714 removal of the volatile water ice may retard sublimation of the underlying ice when the dust is thick

715 enough.

716 As previously described, the complexity of the stratigraphy suggests that minor-order periods  
717 of erosion and deposition also characterized the evolution/growth of the SPLD, possibly driven by  
718 other factors, however barely definable using the available dataset. These minor-order episodes  
719 resulted in the development of local angular unconformities, to which the AUL1 and AUL2 likely  
720 belong, affecting some sections of the PL. As instance, we can suppose that topography might have  
721 locally influenced the deposition and erosion of the SPLD [e.g. *Smith et al.*, 2013] secondary to the  
722 PL1, PL2 and AUR1-AUR2(?) formation. In fact, when SPLD dome accumulated, topographic  
723 relief increased, increasing the likelihood of katabatic wind flow, driven by gravity. These latter are  
724 capable to erode material from the slopes and redeposit it elsewhere. Nevertheless, eventual minor-  
725 order factors of erosion and deposition of PL might suggest that, from place to place, the quantity of  
726 growth/retreat of the SPLD changed in function of local scale factors, however lying within the  
727 same regional context, driven by global factors.

#### 728 **4. Conclusions**

729 We performed a stratigraphic analysis of the SPLD in Promethei Lingula based on the  
730 identification of unconformities, the use of correlative discontinuities and conformities and the  
731 morphologic description of the sequences both in visible images and radargrams. Using techniques  
732 commonly used in Earth-based studies, this approach constrains the stratigraphy of the region and  
733 tries to reduce the amount of possible ambiguous interpretations that are exclusively based on  
734 “morpho-stratigraphy”. In this regard, our approach is an attempt to bypass the problems related to  
735 the morphologic and radiometric appearance of the layers. Thus, it does not exclude diverse  
736 classifications but complements them, whereas other stratigraphic analyses are doubtful, awkward  
737 or impossible to define.

738 We identify two main depositional events that formed two stratigraphic units, named PL1 and  
739 PL2; these are interrupted by one main erosional or non-depositional phase marked by the  
740 discontinuity AUR1. Subsequently, less extensive events partially eroded the PL2, possibly forming

741 the AUR2 discontinuity, and then formed the Aa2 unit [Kolb and Tanaka, 2006], which is almost  
742 entirely located outside the PL ice sheet. Both radar datasets and visible images are consistent with  
743 this interpretation, which supports and extends to the entire PL region the stratigraphy proposed by  
744 Kolb and Tanaka [2006] for the areas of Australi Sulci and Promethei and Ultimum Chasmata.  
745 Thus, the PL1 and PL2 sequences have the rank of major-order units (i.e., Synthems) because the  
746 AUR1 makes them mappable at regional scale. Secondary members within major-order units  
747 cannot be defined through allostratigraphic criteria.

748 In optical images, the lower PL1 is characterized by a prevalent “ridge and trough” (RTS)  
749 [Malin and Edgett, 2001] morphology, given by a succession of thin layers having diverse erosional  
750 strengths and brightness. The upper PL2 is characterized primarily by a “stair-stepped” morphology  
751 (SSS) [Malin and Edgett, 2001] and is outlined by thicker layers than in the PL1, with no evident  
752 variations in brightness or erosional textures. However, at the regional scale, the PL2 has a slight  
753 lateral variability in morphology, showing minor-order “ridge and trough” sequences in some  
754 locations (e.g., Chasma Australe).

755 The AUR1 is also inferable in several radargrams at SHARAD wavelengths. Both PL1 and  
756 PL2 sequences show bright reflectors and horizontal non-reflective zones.

757 The PL stratigraphy supports the hypothesis of time-varying climatic conditions at polar  
758 latitudes that controlled the SPLD geologic history. These climatic conditions are marked by  
759 alternating depositional and erosional/not depositional stages and possibly also by changes in the  
760 depositional pattern and erosional style of the PL1 and PL2 units. The quasi-cyclical variation of  
761 some orbital parameters (such as the variation of the obliquity of the Martian rotational axis) may  
762 have determined climate changes. In particular, the AUR1 formed during high angle orbital axis  
763 [e.g., Costard *et al.* [2002], causing a high insolation of the SPLD surface. In this regard: 1) The  
764 main-order stratigraphy of each PL unit (PL1 and PL2) originated under one long-period insolation  
765 period, forced by one broad variation in Martian obliquity. From high to low obliquity, the erosion  
766 progressed to deposition. From low to high obliquity, deposition progressed to erosion. It is

767 possible that this long-period insolation period was affected by a positive feedback interaction with  
768 other shorter-period orbital variations. 2) During the occurrence of the first episode, the AUR1  
769 erosional surface formed under increasing obliquity [Jarosky *et al.*, 1995; Milkovich and Head,  
770 2005] and causing regional-scale erosion of the PL1. 3) During the main-order insolation periods,  
771 minor-order orbital variations affected the deposition of the PL1 and PL2, resulting in multiple sub-  
772 sequences [e.g., Milkovich and Head, 2005] and possibly local-scale unconformities (e.g., the  
773 AUL1/AUL2) or depositional lags. 4) A third insolation half-cycle (from high to low obliquity)  
774 deposited the Aa2 unit and brought the planet to present-day conditions (low-obliquity period).

775 In conclusion, the present study proposes a simple model of SPLD formation at the PL regional  
776 scale due to alternating depositional and erosional stages and driven by climate changes due to  
777 orbital variation. In this way, main-order sequences, in turn related to geologic controlling factors,  
778 are defined. Given the complexity of the SPLD stratigraphy, several minor-order distinct periods of  
779 accumulation and erosion can be (and have been) defined using different approaches, also in other  
780 regions of the southern ice dome [e.g., Milkovich and Plaut, 2008; Limaye *et al.*, 2012], completing  
781 the overall description of the SPLD stratigraphy in the Planum Australe.

782

## 783 **Acknowledgments**

784 Our research was funded by the Italian Space Agency (ASI) and the Italian Ministry of  
785 University and Research (MIUR). This manuscript was completed and implemented thanks to the  
786 National Centers of Competence in Research (NCCRs) PlanetS grant. The authors wish to thank the  
787 International Space Science Institute (ISSI, Bern, Switzerland) for the kind hospitality during the  
788 preparation of part of this manuscript. We are in debt also to Dr. Monica Pondrelli and Prof. Gian  
789 Gabriele Ori (IRSPS, Università d'Annunzio, Pescara, Italy), and to Dr. Simone Silvestro (SETI  
790 Institute, CA, USA) for the constructive discussions and advices. Special thanks to the Italian  
791 SHARAD team for the acquired data and for the support to our work. We also greatly thank two  
792 anonymous reviewers for their constructive comments and suggestions that substantially improved



793 the manuscript.

794

795 **References**

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1089 **Figure 1.** (a) Location and type of the mapped discontinuities in optical images and radargrams.  
1090 Analyzed stratigraphic exposures are labeled from L1 to L21; red crosses are outcrops affected by  
1091 angular unconformities; white crosses are outcrops showing uncertain angular unconformities.  
1092 Solid red and white lines (1-27) represent the approximated plan-view projection of subsurface  
1093 angular unconformities observed in SHARAD radargrams (TO are transversal orbits). Dotted  
1094 orange inset highlights the type section location (L7). Dotted white inset enclose the main area  
1095 affected by radar angular unconformities (cf. Section 2). Topographic sections NS(w), NS(e) and  
1096 EW (white T symbols) are referred to Fig. 15. (b) MOLA gridded topography of PL region. (c) a-a'  
1097 topographic section of PL (figure b for location). The region has a maximum thickness of about  
1098 1000-1500 m (uncertainties are due to the buried bedrock elevation).  
1099 Credits: MOLA 512 pix/degree and shaded relieves.

1100  
1101 **Figure 2.** a) Observed angular unconformity and mapped correlative discontinuity/conformity  
1102 (AUR1; cf. Section 3.1) in section L7 (cf. Tab. 1); b, c) Narrow-scale view, not-mapped (b) and  
1103 mapped (c) of the exposed angular unconformity. The white arrow indicates the dip direction of the  
1104 scarp (i.e., the direction toward which the topographic elevation decreases). The torch in the upper  
1105 right of images indicates the direction of illumination of the image.  
1106 Credits: a) HRSC nd3 H2169\_0000; b, c) CTX P13\_006290\_1017, P11\_005222\_1021 (in (b) the  
1107 image is contrast-enhanced; in (c) the image has inverted brightness).

1108  
1109 **Figure 3.** a) Broad-scale location of observed angular unconformity and mapped correlative  
1110 discontinuity (AUR1; cf. Section 3.1) exposed along Ultimium Chasma scarps (L18; cfr. Tab. 1). b,  
1111 c) Narrow-scale view, not-mapped (b) and mapped (c) of the angular unconformity exposed in the  
1112 L18 log.  
1113 Credits: CTX P12\_00563\_1006. Image (c) is contrast-enhanced.

1114

1115 **Figure 4.** a) Broad-scale location of observed angular unconformity and mapped correlative  
1116 discontinuity (AUR1; cf. Section 3.1) exposed along Promethei Chasma scarps (L20; cfr. Tab. 1). b,  
1117 c) Narrow-scale view, not-mapped (b) and mapped (c) of the angular unconformity exposed in the  
1118 L20a log.

1119 Credits: CTX B08\_012710\_0966. Image (b) is contrast-enhanced.

1120

1121 **Figure 5.** Subsurface angular unconformity AUR1 dividing two sets of radar bright reflectors  
1122 characterized by different dipping angle, consistent with the exposed RTS and SSS sequences.  
1123 Some of them are clearly truncated by the unconformable surface. The transition between the two  
1124 sequences is in some cases marked by low intensity reflections zones ~100 m thick that rests upon  
1125 the unconformities when present (letter A in figure). The topographic surface is located around the  
1126 average MOLA elevation of ~2300 m (black and blue dashed line).

1127 Credits: SHARAD along-track radargram, orbit rdr0938801 (cf. red line 24 in Fig. 1a and Tab. 2).  
1128 Vertical depth is calculated assuming permittivity ( $\epsilon$ ) equal to 3.4 (~ice mean and dust particles).

1129

1130 **Figure 6.** a, b) Subsurface angular unconformity AUR1 dividing two set of radar reflectors  
1131 characterized by different dipping, consistent with the exposed RTS and SSS sequences (a, not-  
1132 mapped; b, mapped). Some of them are clearly truncated by the unconformable surface. The  
1133 transition between the two sequences is in some cases marked by low intensity reflections zones  
1134 ~100 m thick that rests upon the unconformities when present (letter A in figure); c) MOLA  
1135 topographic cross section of the AB segment. As reference, the average elevation of the surface is  
1136 around 2300 m.

1137 Credits: SHARAD along-track radargram, orbit rdr0220201 (cf. red line 1 in Fig. 1a and Tab. 2).  
1138 (b) radargram is radiometrically inverted. Vertical depth is calculated assuming permittivity ( $\epsilon$ )  
1139 equal to 3.4 (~ice mean and dust particles).

1140

1141 **Figure 7.** a, b) Subsurface angular unconformity AUR1 on radargram crosscutting orbits in figures  
1142 5 and 6 and dividing two set of radar reflectors, consistent with the exposed RTS and SSS  
1143 sequences. Also in this case some radar reflectors are (with some uncertainty) characterized by  
1144 different dipping angle (a, not-mapped; b, mapped); c) MOLA topographic cross section of the AB  
1145 segment. As reference, the average elevation of the surface is around 2300 m.  
1146 Credits: SHARAD along-track radargram, orbit rdr0673001 (cf. white TO line 19 in Fig. 1a and  
1147 Tab. 2). (b) radargram is radiometrically inverted. Vertical depth is calculated assuming  
1148 permittivity ( $\epsilon$ ) equal to 3.4 (~ice mean and dust particles).

1149  
1150 **Figure 8.** 3D-view of the subsurface radar AUR1 plane (cf. Fig. 1a for location and Section 2.2).  
1151 The DEM shows an irregular and continuous discontinuity surface, roughly decreasing in elevation  
1152 (i.e., dipping) toward SE. The DEM has been obtained from the interpolation of sample elevation  
1153 points (representing the minimum, the intermediate and the maximum elevation of each radar-  
1154 observed unconformity in each radargram), using Kriging method. Each point is, thus, defined by  
1155 latitude, a longitude and an elevation, this latter obtained subtracting, in each radar orbit, the  
1156 average elevation of the surface from the respective measured depth from the surface of the point.

1157  
1158 **Figure 9.** a, b) Subsurface angular unconformity AUR1 (a, not-mapped; b, mapped) dividing two  
1159 set of radar reflectors characterized by different dipping angle, consistent with the visible RTS and  
1160 SSS sequences. It is located in correspondence of the type section L7b, where the AUR1 is  
1161 exposed. The top sequence appears to have reflectors interrupted by the inferred unconformity; c)  
1162 MOLA topographic cross section of the AB segment. As reference, the average elevation of the  
1163 surface is around 2400 m.  
1164 Credits: SHARAD along-track radargram, orbit rdr0656701 (line 17 in Fig. 1a and Tab. 2). (b)  
1165 radargram is radiometrically inverted. Vertical depth is calculated assuming permittivity ( $\epsilon$ ) equal to  
1166 3.4 (~ice mean and dust particles).

1167

1168 **Figure 10.** Topographic profile from MOLA gridded data of the type section (L7b) and dip-angle  
1169 of the scarp. The stratigraphic boundary between the RTS and SSS sequences, coinciding with the  
1170 discontinuity plane AUR1, is in some cases marked by a slight change in the topographic gradient  
1171 of the profile. On the right is reported the stratigraphic section of the sequence.

1172

1173 **Figure 11.** Stratigraphic type section (L7b), not mapped (a) and mapped (b). The dashed white  
1174 inbox indicates the location of Figs. 10-12. Cf. Section 2 for a detailed description of the  
1175 stratigraphy.

1176 Credits: CTX P10\_005103\_0995. Image (a) is contrast-enhanced.

1177

1178 **Figure 12.** Focus on type section stratigraphy (L7b). a) The discontinuity AUR1 spaces out a  
1179 layered “stair-stepped” top sequence (SSS; left on the image) from a thin layered “ridge and  
1180 trough” bottom sequence (RTS; right on the image). The contact between the two sequences is  
1181 marked by the presence of benched layers (Bn) within the RTS; b) Detailed view of the RTS  
1182 layering (Rg: ridge shaped layers, bright and convex-upward in section view; Tr: trough shaped  
1183 layers, dark and concave-upward in section view; Ly is to indicate an example location of sub-  
1184 metric layering, only visible at HiRISE resolution); c) Detailed view on a benched layer, showing  
1185 notched edges (Ne in figure (a) as example).

1186 Credits: HiRISE PSP\_004655\_1005.

1187

1188 **Figure 13.** Focus on type section stratigraphy (L7b). Detailed view of the SSS layering, mostly  
1189 characterized by benched layer (Bn), in some cases showing notched edges (Ne as example).

1190 Credits: CTX P10\_005103\_0995.

1191

1192 **Figure 14.** Correlation of the L7b type section (a; PL margins) with two stratigraphic exposures of



1193 example, located in Chasma Australe (b; L5) and Ultimum Chasma (c; L18; cf. Fig. 1a for  
1194 location), through the regional discontinuity AUR1, spacing out the PL1 and PL2 units. The PL1  
1195 maintains the RTS morphology in all the outcrops, but it can differ from the type section mainly in  
1196 terms of thickness (several pinch-out closure of sub-sequences are inferable across the region). The  
1197 PL2 is mostly characterized by benched layers (SSS morphology), but it can include also thinner  
1198 “ridge and trough” layering, especially in exposures located at the borders with Ultima Lingula and  
1199 Australe Lingula regions (see section c as an example). This is consistent with conventional  
1200 stratigraphy on Earth (Salvador, 1987; Catuneanu, 2006), in which discontinuities are used to  
1201 correlate and define discontinuity-bounded sequences irrespectively of their eventual morphological  
1202 or lithological lateral changes in the depositional environment.

1203

1204 **Figure 15.** Regional stratigraphy of the SPLD sequence in PL, represented, in each figure, through  
1205 logs correlation using the regional discontinuities and along three topographic profiles (from top to  
1206 bottom respectively NS(w), NSe, EW; cf. Fig. 1a for logs location and Section 3 for detailed  
1207 analysis). With gray-borders are represented logs obtained from radargrams. Logs with dashed  
1208 borders are not located along the topographic profile but projected from locations close to it. To  
1209 note the slight dip (i.e., decrease of the mean elevation) toward PL margins of the discontinuity  
1210 AUR1. The elevation of the buried bedrock (i.e., the SPLD base) is not measured, but it has been  
1211 obtained through interpolation from exposed outcrops around the ice-sheet. The elevation of the  
1212 buried bedrock is consistent with the elevation calculated through MARSIS and SHARAD [Plaut *et*  
1213 *al.*, 2007]. Cf. Tab. 1 and 2 for stratigraphic logs details. PL = Promethei Lingula; UL = Ultima  
1214 Lingula; AL = Australe Lingula; UC = Ultimum Chasma; PC = Promethei Chasma; CA = Chasma  
1215 Australe.

1216

1217 **Figure 16.** Proposed geologic scenario and chronology of the main events characterizing the SPLD  
1218 in PL (the topographic profile is referred to the type section L7b). According to our analysis, the PL

1219 region has been affected by two main depositional stages (D1 and D2 in the scheme), setting the  
1220 PL1 and PL2 units, and one main erosional/not depositional stage (E1) of regional scale, removing  
1221 part of the PL1 unit and modeling the unconformity AUR1. A further erosional/not depositional  
1222 phase (E2) partially removed the PL2 (AUR2). Erosion likely took place mainly through wind  
1223 abrasion and sublimation. During time 1 and 2, local melting of the PL ice-sheet cannot be  
1224 excluded, as possibly suggested by broad “soft-sediment” deformational systems observed in some  
1225 locations [Guallini *et al.*, 2012]. These events were likely forced by periodic climatic changes that  
1226 in turn were driven by variations in the obliquity of the planet. Later depositional phases (D3)  
1227 would have deposited the Aa2 unit, unconformable resting upon the PL2 through the AUR2  
1228 discontinuity, but involving only marginally the PL region. The attitude of the drawn layering  
1229 (white or black lines) is not real and just aimed to show the possible angular unconformity between  
1230 the PL1 and PL2 sequences.

1231

**Table 1.** Discontinuities mapped in visible images

Log Id	Lat ( <i>South</i> )	Lon ( <i>East</i> )	Elevation ( <i>km</i> ) <sup>a</sup>	Length ( <i>km</i> ) <sup>b</sup>	Imager Type <sup>c</sup>	Imagery Id <sup>e</sup>	Disc Type <sup>d</sup>	Disc Id	Bounded Sequences <sup>e</sup>	Location <sup>f</sup>	Cf. Fig.
L1*	82.53	91.26	1.4	n.d.	HRSC	h2169	AU?	n.d.	n.d.	CA	-
L2	85.45	97.56	2.4-2.5	5	HiRISE	PSP_004933_0945	AU?	AUR2?	Aa2/SSS	CA	-
L3*	85.20	98.16	1.5	n.d.	CTX	P10_005082_0851	AU?	n.d.	n.d.	CA	-
L4*	85.19	98.30	1.8	n.d.	CTX	P10_005082_0851	AU?	n.d.	n.d.	CA	-
L5a	84.57	99.42	1.7-2	75	CTX	P10_005082_0851	CC	AUR1	SSS/RTS	CA	-
L5b	84.36	101.30	1.7-2		CTX	P10_005082_0851	CC	AUR1	SSS/RTS	CA	-
L6	80.32	94.25	1.45	30	CTX HRSC	B06_011828_0996 h2069	AUn CC	AUR1? AUR1?	SSS?/RTS?	PL	A1a,b
L7a	79.49	100.53	1.7-2	122	CTX	P09_004708_0998	AU	AUR1	SSS/RTS	PL	-
<b>L7b<sub>g</sub></b>	<b>79.31</b>	<b>102.23</b>	<b>1.7-1.8</b>		<b>CTX</b>	<b>P13_006290_1017</b> <b>P11_005222_1021</b>	<b>CC</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>PL</b>	<b>2,11,12,13</b>
L7c	80.32	100.10	1.9-2.2		CTX	B05_011762_0997	CD	AUR1	SSS/RTS	PL	-
L8*	79.11	105.49	1.4	n.d.	HiRISE	PSP_004374_1005	Au?	AUL1?	n.d.	PL	-
L9a	79.14	107.47	1.6-2	53	CTX	P05_003078_0786	CC	AUR1	SSS/RTS	PL	-
L9b	79.31	108.19	1.5-1.7		CTX	P05_003078_0786	AUn CD	AUR1	SSS/RTS	PL	A1b,c
L10a	80.50	112.33	1.6-2.0	25	CTX HRSC	B12_014280_0989 h2440	AU	AUR1	SSS/RTS	PL	A2a,b
L10b	80.78	117.04	2.1-2.2	n.d.	CTX	P10_005103_0995	CD	AUR1	SSS/RTS	PL	-
L11*	80.00	112.42	1.5	n.d.	CTX HRSC	P10_004826_1013 h2440	AU?	AUL1?	n.d.	PL	-
L12*	79.14	111.60	2.3	n.d.	CTX	B11_013779_1006	AU?	AUL2?	Aa2?/SSS	PL	-
L13	78.30	117.20	1.85-2.1	27	CTX	P12_005617_1011	AUn CD	AUR1	SSS/RTS	PL	A2b,c
L14*	79.15	124.45	2.2	n.d.	CTX	B09_013251_1002	AU?	AUL2?	n.d.	PL	-
L15a	79.36	132.13	1.6-1.7	70	CTX HRSC	B08_012842_1023 h2330	AU CD	AUR1	SSS/RTS	UC	A3a,b
L15b	79.20	130.48	1.6-1.7		CTX HRSC	P10_004799_0998 h2330	AU CD	AUR1	SSS/RTS	UC	A3a,b
L16*	81.30	144.0	1.4	n.d.	CTX	B07_012367_099	AU?	n.d.	n.d.	UC	-

0			4								
L17	81.11	147.1 0	1.3-2.2	33	CTX	B08_012802_098 3	AU CD	AUR1	SSS/RTS	UC	A3c,d
L18	80.56	150.5 4	1.6-2.1	92	CTX HRSC	P12_005603_100 6 h2348	AU CD	AUR1	SSS/RTS	UC	3
L19*	82.16	163.1 8	1.9	n.d.	HiRISE	PSP_006288_097 5	AU?	AUR1 ?	SSS?/RTS ?	UC	-
L20 a	82.28	142.5 0	2.1-2.2	59	CTX	B08_012710_096 6	AU	AUR1	SSS/RTS	PC	4
L20 b	81.52	141.8 0	2.1-2.2		CTX	B08_012710_096 6	CD	AUR1	SSS/RTS	PC	4
L21*	84.00	149.2 5	1.6	n.d.	CTX	B08_012710_096 6	AU?	n.d.	n.d.	PC	-

\* Uncertain discontinuity

<sup>a</sup> Approximate elevation range (min-max)

<sup>b</sup> Approximate mapped length (n.d. = not determinable)

<sup>c</sup> Reference type image(s) and number

<sup>d</sup> AU = Angular Unconformity; CD = Correlative Discontinuity; CC = Correlative Conformity; n.d. = not determinable

<sup>e</sup> “Discontinuity-Bounded” Sequences (cf. Section 2)

<sup>f</sup> Geographic location of the discontinuities (PL = Promethei Lingula; CA = Chasma Australe; UC = Ultima Chasma; PC= Promethei Chasma

<sup>g</sup> Type Section

**Table 2.** Angular unconformities mapped in radargrams

Log Id <sup>a</sup>	Lat S (Init) <sup>b</sup>	Lat S (End) <sup>b</sup>	Lon E (Init) <sup>b</sup>	Lon E (End) <sup>b</sup>	Length (km) <sup>c</sup>	Elevation (m) <sup>d</sup>	Disc Type <sup>e</sup>	Disc Id	Bounded Sequences <sup>f</sup>	SHARAD Orbit Id <sup>g</sup>	Cf. Fig.
<b>1(1)</b>	<b>82.85S</b>	<b>118.80E</b>	<b>81.16S</b>	<b>114.26E</b>	<b>150</b>	<b>1700</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0220201</b>	<b>6</b>
2(1)	82.38S	116.82E	81.16S	114.26E	80	1900-2100	AU	AUR1	SSS/RTS	rd0241301	A10
3(1)	82.66S	117.09E	81.25S	113.37E	90	1900-2000	AU	AUR1	SSS/RTS	rd0262401	-
4(1)	82.77S	116.81E	81.22S	112.67E	98	1900-2100	AU	AUR1	SSS/RTS	rd0283501	-
5(1)	82.99S	116.78E	81.17S	111.75E	100	1900-2100	AU	AUR1	SSS/RTS	rd0325701	-
<b>6(1)</b>	<b>82.32S</b>	<b>111.95E</b>	<b>81.48S</b>	<b>114.09E</b>	<b>54</b>	<b>1800?</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0331501</b>	-
<b>7(1)</b>	<b>84.77S</b>	<b>106.81E</b>	<b>83.16S</b>	<b>114.51E</b>	<b>109</b>	<b>2300?</b>	<b>AU</b>	<b>AUR2?</b>	<b>Aa2/SSS?</b>	<b>rd0332801</b>	-
8(1)	83.26S	117.43E	81.16S	111.41E	120	1800-2000	AU	AUR1	SSS/RTS	rd0346801	-
9(1)	82.98S	115.84E	81.16S	110.82E	115	1850-2100	AU	AUR1	SSS/RTS	rd0367901	A11
10(1)	82.95S	114.71E	81.55S	110.68E	91	1800-2000	AU	AUR1	SSS/RTS	rd0410101	-
<b>11(1)</b>	<b>83.00S</b>	<b>119.84E</b>	<b>82.02S</b>	<b>122.74E</b>	<b>64</b>	<b>1800?</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0411901</b>	-
<b>12(1)</b>	<b>82.76S</b>	<b>113.70E</b>	<b>81.35S</b>	<b>117.42E</b>	<b>93</b>	<b>1950-2150</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0417201</b>	-
<b>13(3)</b>	<b>80.46S</b>	<b>151.95E</b>	<b>78.87S</b>	<b>149.46E</b>	<b>99</b>	<b>2100?</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0428401</b>	-
14(1)	84.27S	128.19E	81.66S	118.71E	170	1600-1900	AU	AUR1	SSS/RTS	rd0440401	-
<b>15(1)</b>	<b>83.17S</b>	<b>115.05E</b>	<b>81.77S</b>	<b>119.17E</b>	<b>92</b>	<b>2000-2100</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0446201</b>	<b>A12</b>
<b>16(1)</b>	<b>83.05S</b>	<b>111.82E</b>	<b>81.51S</b>	<b>116.16E</b>	<b>72</b>	<b>1950-2150</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0459401</b>	-
17(2)	81.63S	104.81E	79.92S	101.32E	107	1700-2250	AUn	AUR1	SSS/RTS	rd0656701	12
<b>18(1)</b>	<b>82.88S</b>	<b>113.80E</b>	<b>81.61S</b>	<b>117.31E</b>	<b>81</b>	<b>2000</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0658501</b>	-
<b>19(1)</b>	<b>83.00S</b>	<b>114.32E</b>	<b>81.60S</b>	<b>118.28E</b>	<b>91</b>	<b>2000-2100</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0673001</b>	<b>7</b>
<b>20(1)</b>	<b>82.61S</b>	<b>112.39E</b>	<b>81.35S</b>	<b>115.69E</b>	<b>81</b>	<b>1800-2000</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0700701</b>	-
<b>21(1)</b>	<b>82.49S</b>	<b>110.67E</b>	<b>80.94S</b>	<b>114.48E</b>	<b>98</b>	<b>1800?</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd0707301</b>	-
22(1)	83.26S	122.00E	81.74S	117.27E	98	1700	AU	AUR1	SSS/RTS	rd0896601	-
23(1)	82.43S	119.67E	81.16S	116.42E	130	1750	AU	AUR1	SSS/RTS	rd0932201	-
24(1)	82.42S	117.86E	81.46S	115.17E	100	1800-1900	AU	AUR1	SSS/RTS	rd0938801	5
25(2)	81.56S	104.04E	79.99S	100.82E	98	1700-2250	AU	AUR1	SSS/RTS	rd1056201	-
<b>26(1)</b>	<b>82.96S</b>	<b>114.90E</b>	<b>81.70S</b>	<b>118.44E</b>	<b>115</b>	<b>2000-2100</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd1610501</b>	-
27(1)	83.85S	125.57E	81.77S	118.62E	180	1600-2100	AU	AUR1	SSS/RTS	rd1640301	-
<b>28(2)</b>	<b>83.01S</b>	<b>102.35E</b>	<b>81.18S</b>	<b>107.27E</b>	<b>81</b>	<b>1800-1900</b>	<b>AU</b>	<b>AUR1</b>	<b>SSS/RTS</b>	<b>rd1614501</b>	-

Bold rows are transversal orbits crossing longitudinal orbits.

<sup>a</sup> Numbers identify single observed unconformities. In parenthesis are reported the identification numbers of orbits displaying the angular unconformity in the same location.

<sup>b</sup> Approximate beginning and end of the unconformities, projected on surface in plan-view (cf. Fig. 1a)

<sup>c</sup> Approximate mapped length

<sup>d</sup> Approximate elevation range (min-max)

<sup>e</sup> AU = Angular Unconformity

<sup>f</sup> “Discontinuity-Bounded” Sequences (cf. Section 2)

<sup>g</sup> SHARAD reference orbit











































